Northumbria Research Link

Citation: Han, Chong, Dianati, Mehrdad, Cao, Yue, McCullough, Francis and Mouzakitis, Alexandros (2019) Adaptive Network Segmentation and Channel Allocation in Large scale V2X Communication Networks. IEEE Transactions on Communications, 67 (1). pp. 405-416. ISSN 0096-1965

Published by: IEEE

URL: https://doi.org/10.1109/TCOMM.2018.2868080 <https://doi.org/10.1109/TCOMM.2018.2868080>

This version was downloaded from Northumbria Research Link: http://nrl.northumbria.ac.uk/id/eprint/36100/

Northumbria University has developed Northumbria Research Link (NRL) to enable users to access the University's research output. Copyright © and moral rights for items on NRL are retained by the individual author(s) and/or other copyright owners. Single copies of full items can be reproduced, displayed or performed, and given to third parties in any format or medium for personal research or study, educational, or not-for-profit purposes without prior permission or charge, provided the authors, title and full bibliographic details are given, as well as a hyperlink and/or URL to the original metadata page. The content must not be changed in any way. Full items must not be sold commercially in any format or medium without formal permission of the copyright holder. The full policy is available online: http://nrl.northumbria.ac.uk/policies.html

This document may differ from the final, published version of the research and has been made available online in accordance with publisher policies. To read and/or cite from the published version of the research, please visit the publisher's website (a subscription may be required.)

Northumbria University NEWCASTLE

CUSTOMER SERVICE EXCELLENCE CSE UniversityLibrary

Adaptive Network Segmentation and Channel Allocation in Large-scale V2X Communication Networks

Chong Han, *Member, IEEE,* Mehrdad Dianati, *Senior Member, IEEE,* Yue Cao, *Member, IEEE,* Francis Mccullough, and Alexandros Mouzakitis

Abstract

Mobility, node density and the demand for large volumes of data exchange have aggravated competition for limited resources in the wireless communications environment. This paper proposes a novel MAC scheme called Segmentation MAC (SMAC) which can be used in large-scale Vehicle-to-Everything (V2X) communication networks. SMAC functions to support the dynamical allocation of radio channels. It is compatible with the asynchronous multi-channel MAC sub-layer extension of the IEEE 802.11p standard. A key innovate feature of SMAC is that the segmentation of the network and channel allocations are dynamically adjusted according to the density of vehicles. We also propose a novel efficient forwarding mechanism to ensure inter-segment connectivity. To evaluate the

C. Han and M. Dianati are with the Institute for Communication Systems (ICS), 5G Innovation Centre (5GIC), University of Surrey, United Kingdom, GU2 7XH (e-mail: {chong.han, m.dianati}@surrey.ac.uk).

Y. Cao is with the Department of Computer and Information Sciences, Northumbria University, Newcastle upon Tyne, UK, (e-mail: yue.cao@northumbria.ac.uk).

F. Mccullough and A. Mouzakitis are with Jaguar Land Rover, Whitley, Coventry, United Kingdom, CV3 4LF (email: {fmccull2, amouzak1}@jaguarlandrover.com).

performance of inter-segment connectivity, a rigorous analytical model is proposed to measure the multi-hop dissemination latency. The proposal is evaluated in network simulator NS2 as well as the standard IEEE 1609.4 and two asynchronous multi-channel MAC benchmarks. Both analytical and simulation results demonstrate better effectiveness of the proposed scheme compared with existing similar schemes in the literature.

Index Terms

Large-scale systems, Multiaccess communication, Adaptive systems, Communication channels, Resource management.

I. Introduction

Recent research [1] reports that Vehicle-to-Vehicle (V2V) technology based on Dedicated Short Range Communication (DSRC) using the standard IEEE 802.11p [2] will be introduced in new/autonomous vehicles, resulting a high penetration rate (61.8%) of V2X by 2027. Meanwhile, in the vision for future automotive industry [3], use cases rely on high data rate of information exchange (e.g., some vary from 10 to 40 Mbit/s per use case per vehicle). The challenges in terms of node density, frequent/competitive channel access due to high mobility, and large volumes of traffic flows are therefore intuitively foreseeable in V2X communications. Hence, there is an urgent call for a more efficient MAC scheme enabling V2X communications in the future dense large-scale vehicular networks. To this end, this paper proposes a novel multi-channel MAC scheme to tackle this problem.

In the last decade, to mitigate the starvation multi-channel extension of the standard IEEE 802.11p [2] MAC sub-layer, i.e., IEEE 1609.4 multi-channel operation [21], was proposed. IEEE 1609.4 improves the performance by allocating a dedicated channel for control signalling and allowing simultaneous communications over multiple service channels. The IEEE 1609.4 extension adopts a synchronous switching between control channel and service channels. It is shown that synchronous operation of the MAC sub-layer is an inherently poor utilisation of the bandwidth ([11], [23], [24]). To mitigate the poor bandwidth utilisation problem of synchronous multi-channel MACs, asynchronous multi-channel MACs were proposed (surveyed in [17]). This was further enhanced by introducing hopping sequence to schedule multiple parallel rendezvous [18], applying Pulse/Tone exchanges prior to handshake for collision avoidance on the control channel [19]. In our previous work [11], we proposed a novel distributed asynchronous multi-channel MAC scheme in favour of high network load and multiple simultaneous transmissions via Distributed-TDMA mechanism and enhanced channel utilisation. It outperforms well-known existing asynchronous multi-channel MAC schemes such as [7], [8] and [21]. It was demonstrated that this scheme improves system performance in terms of the overall system throughput, packet delivery rate, collision rates on service channels, load balancing, and service differentiation.

However, none of these aforementioned ([7], [8], [11], [18] and [19]) asynchronous multi-channel MAC schemes address the challenges arising from large-scale networks, i.e., achieving comparable system performance as they do in single-hop scenarios ([4], [5], [6]). Simulation results from both literature [4] and this work (as shown in Sec. V) reveal that existing multi-channel MAC schemes suffer from severely poor bandwidth utilisation, packet delivery and dissemination. This is mainly associated with the high level of contention and limited spatial reuse [13], due to the over-protective Clear Channel Assessment (CCA) mechanism.

In this paper, we propose an efficient MAC scheme for large-scale dense networks, that can work on top of asynchronous multi-channel MAC schemes, such as [7], [8] and [11]. The proposed technique exploits cooperation of infrastructures such as Road Side Units (RSUs) and centralised network controlling server. The centralised controller dynamically makes decisions to segment the large-scale network into multiple serving areas, and efficiently allocates control and service channels across the entire network. The concept of network segmentation has been previously employed in [14], [15], [16]. It is worth noting that different from existing work, this proposed segmentation approach adapts to the network status (e.g., node density) and integrates with the asynchronous multi-channel extensions of the IEEE 802.11p MAC sub-layer. When a network is segmented and different sets of channels are used within different segments, inter-segment communications cannot be naturally carried out. We therefore also propose an effective technique for communications among the nodes in different segments of the network. In addition, a rigorous analytical model is developed to analyse the performance of inter-segment dissemination of critical messages. Finally, extensive simulation results under realistic assumptions using Network Simulator 2 (NS2) [22] environment are given to validate the accuracy of the proposed analytical models and evaluate the performance of the proposed technique. Both the simulations results and the analytical models demonstrate that the proposed scheme outperforms benchmark multi-channel MAC schemes [21], [8] and [11] in large-scale dense vehicular networks, in terms of (aggregate/normalised) throughput, multi-hop dissemination delay (i.e., end-to-end delay between two nodes in non-adjacent segments), and the fast penetration capability[1].

The rest of the paper is organized as follows. First, key entities in the system and the connections among them are briefly introduced in Section II. The proposed scheme is then elaborated with details in Section III. Analytical models with regard to the inter-segment dissemination mechanisms in multi-hop scenarios are proposed and validated in Section IV. Simulation based performance evaluation is given in Section V. Finally, Section VI concludes the paper.

II. System Model

This section presents applicable scenarios for the proposal. As shown in Fig. 1, such V2X communication systems shall consist of vehicles, RSUs and a Network Control Server (NCS). Vehicles and RSUs are equipped with DSRC network interfaces for V2X communications, that employ an asynchronous multi-channel MAC technology which is described later in this section. V2X communication interfaces enable Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) communications. In addition, vehicles are considered to be equipped with Global Positioning System (GPS) enabling them to obtain their locations.

[1]This concept is introduced in Section V.

Typical RSUs are V2X enabled road infrastructural units. For instance, traffic lights and base stations, mounted with communication and computing devices, could be deemed permanent RSUs [28]. There may be dedicated network interfaces for communications among RSUs and to the network control server, denoted by Infrastructure-to-Infrastructure (I2I) interfaces in Fig. 1, which could be facilitated via cellular systems such as LTE or fiber optic links. Alternatively, a dedicated wireless channel in DSRC could also enable I2I communications among RSUs.

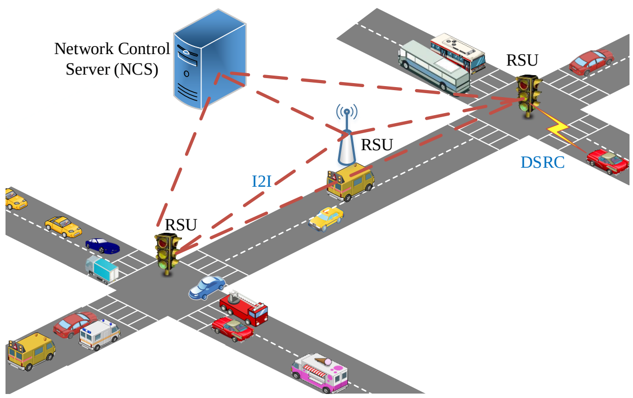

Fig. 1. System Model

NCS processes the information reported by RSUs and makes decision with regard to segmentation management and channel allocation.

The MAC sub-layers of the DSRC network interfaces adopt the IEEE 802.11p standard with a 7-channel asynchronous extended function, namely, Asynchronous Multi-Channel MAC (AMCMAC) [7] scheme. In AMCMAC, nodes tune to the Control Channel (CCH) by default. The CCH is used for channel negotiations and the broadcast of emergency messages. After successful channel negotiation, the pair of nodes hop to the agreed Service Channel (SCH) to finish the transmission of large data packets. Nodes switch back to CCH when the transmission on the SCH is completed.

Vehicles may communicate with each other and RSUs, but not directly with the NCS. The NCS only communicates with RSUs. RSUs collect information from V2X messages sent by vehicles; RSUs periodically report [2] to NCS after data analysis and processing; RSUs also assist the inter-segment communications as well as the dissemination of the segmentation-related information. As the centralised controlling server, NCS gathers information of network status via RSUs. Based on the global knowledge of the network, it makes decisions regarding segmentation and channel allocation. NCS informs each RSU to establish/revoke segmentation and corresponding channels which are allocated to the segment. The establishment and revocation of segmentations are explained with detail in Sec. III.

III. The Proposed Scheme

The proposed solution is introduced with details in this section. First, an overview of the proposed scheme is given. Then, key innovations of the proposed scheme shown in Fig. 2 are described in detail.

At a glance, the scheme relies on the centralised controller NCS. NCS dynamically decides to partition the network or revoke the segmentation, via either the revocation (orange) route or the segmentation (blue) route. When segmentation is decided to be desired for a congested network by monitoring the network status in Segmentation Management, NCS then considers the rules of segmentation. Here, segments are considered as geographical regions in the shape of square, where the corresponding RSU of a particular segment locates at the centre of the square. The size of the segment is determined by both non-overlapping rule and the contention control mechanism. Once segmentation strategies are confirmed, rules in Channel Allocation shall be followed, e.g., the compatiability with existing MAC schemes, interence avoidance, and inter/intra-segment connectivities, in order to efficiently make use of the radio resources. NCS

[2] The frequency of reporting to NCS is not restricted in this paper. Usually, it is assumed that the number of vehicles in the range of each RSU may not change much during a few seconds. Hence, the frequency of report sending is not necessarily higher than 0.1 Hz.

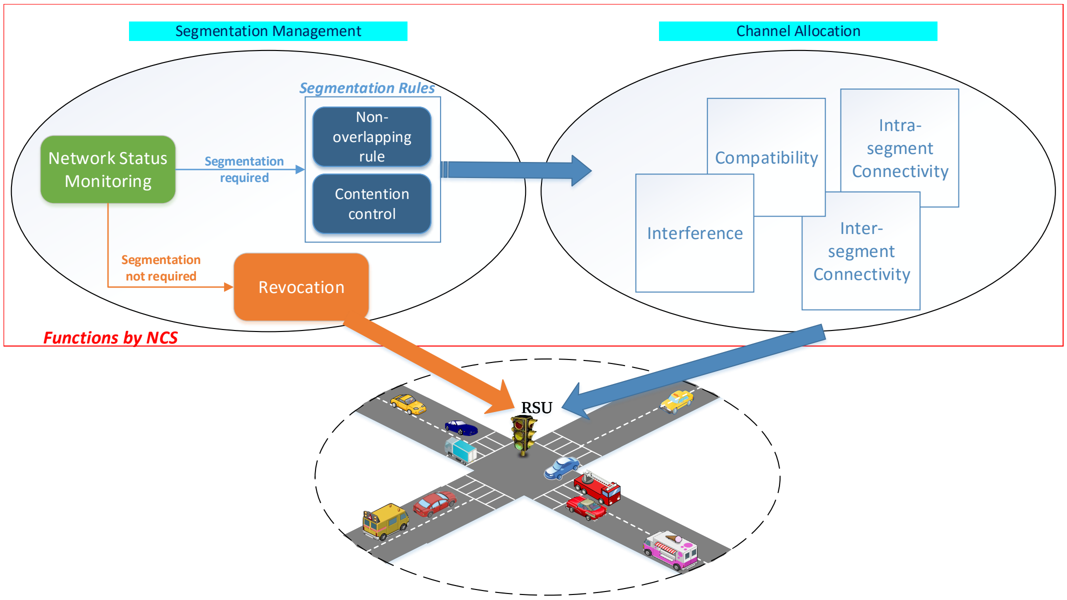

Fig. 2. Key Functions Implemented at NCS for SMAC Scheme

finally informs RSUs the network segmentation strategies as well as allocated channels, adapting to the congestion level in the network. Key designs and features of SMAC are elaborated in the following.

A. Segmentation Management

As shown in Fig. 2, the segmentation management consists of three function blocks, namely the Network Status Monitoring, Segmentation Rules and Revocation. NCS maintains the supervision of the network status in terms of node density around the RSUs. Whenever the necessity of forming segmentations is found, NCS decides the segmentation strategies based on the network status following the segmentation rules. Revocation is self-explanatory, that NCS simply informs relevant RSUs to revoke the segmentation and go back to the defult multi-channel MAC scheme. Thus, the following will focus on the introduction to network status monitoring and rules for segmentation.

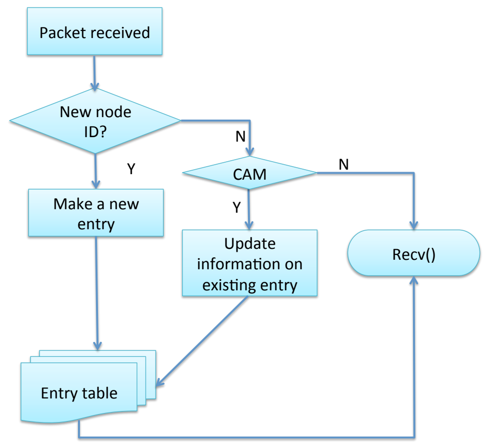

Fig. 3. Network Status Maintenance

*1) **Network Status Monitoring**:* NCS monitors the network status in terms of node density near RSUs based on the periodical reports sent by RSUs. Hence, the first step is for RSUs to monitor the active nodes within their own communication ranges. As shown in the flow chart in Fig. 3, if a vehicle enters the communication range of an RSU for the first time, the RSU obtains the vehicle ID in the packet (e.g., CAM/DENM[3], peer-to-peer messages) received from the vehicle, and then creates a new entry for this vehicle. If the vehicle has been previously recognised and recorded with an existing entry, RSUs update the entry with the up-to-date location information of the vehicle. RSUs maintain their entry tables by adding/removing nodes according to received messages in order to achieve a relatively accurate estimation of surrounding nodes.

In the RSU's report, the number of vehicles (i.e., N_x) in the vicinity of each RSU for different ranges (i.e., within D_x m away from the RSU) are listed. An example of such list is given in Table. I. For instance, for this RSU, there are 50 vehicles within 100m; 80 within 200m and 200 vehicles within 500m.

[3]CAM: Cooperative Awareness Message. DENM: Decentralized Environmental Notification Message.

TABLE I

SAMPLE PERIODICAL REPORT FROM RSUS

Range Index	Range (0-D_Xm)	Number of neighboring vehicles (N_X)
1	0 - 100 m	50
2	0 - 200 m	80
3	0 - 500 m	200
...	...	...

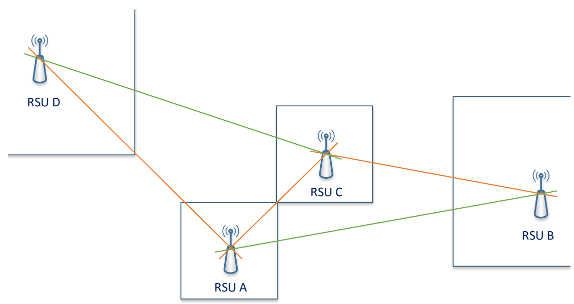

Fig. 4. An Example of Network Segmentation

Potential congestion is identified when the total number of nodes within the communication range of an RSU is greater than a threshold $N_{desired}$ (which value is adjustable according to the focus of the networks/operators),

$$N_x > N_{desired}. \tag{1}$$

When the NCS detects potential congestion in the RSU's report, NCS starts to calculte suitable segment sizes for related RSUs following the two segmentation rules.

*2) **Segmentation Rule 1 - Non-overlapping**:* The basic principle of this rule is to avoid overlapping areas, where nodes inside these areas are allocated with different sets of channels. Fig. 4 gives an example when multiple RSUs are available in a large-scale congested area. Assuming each RSU is surrounded by large number of nodes, the NCS may divide the area into multiple segments around RSUs. Orange lines represent the minimum distance between itself and nearby RSU peers. It can be easily proved that if the maximum size[4] is limited to the minimum distance divided by $\sqrt{2}$, overlapping areas will be avoided. Hence, the maximum size $L_{i_{max}}$ for each segment i is given by:

$$L_{i_{max}} = min(\frac{dist(I,B)}{\sqrt{2}}, \frac{dist(I,C)}{\sqrt{2}}, \frac{dist(I,D)}{\sqrt{2}}, ...), \tag{2}$$

where $dist(x,y)$ is the distance between two adjacent RSUs (i.e., RSU_x and RSU_y). Here, an extreme example is given by RSU A and C, where two adjacent RSUs line up exactly at 45 degree from the horizon. This example gives the reason to decide $L_{i_{max}}$ as in Eq. (2), which aims to allocate the maximum size of segmentation for each RSU and meanwhile to avoid overlapping segments. The importance to avoid overlapping segments is raised by the channel allocation mechanism and discussed in Section III-B in detail.

*3) **Segmentation Rule 2 - Contention Control**:* The NCS also needs to control the contention level for nodes around each RSU utilising the same set of channels. In the reports from RSUs (an example is given in Table. I), a list of numbers of nodes within different ranges is reported to NCS. Here, NCS shall reduce the communication range to the ranges (i.e., D_x) when the number of nodes within the range is no greater than the desired threshold $N_{desired}$. Then, the maximum range D_{max} can be obtained by:

$$D_{max} = max(D_i | N_i \leq N_{desired}), \tag{3}$$

where N_i is the number of nodes within the area ($0 \sim D_i$ m away from the RSU). For instance, as shown in the example in Table. I, 200 nodes appear around the RSU within 500 m; 80 nodes within 200 m; and 50 nodes within 100 m away from the RSU. If the threshold $N_{desired}$ is 100, 200 m will be chosen as the D_{max} to ensure the number of surrounding nodes is under

[4]The size of each segment is defined by the length of sides (i.e., L) for each segment.

the threshold 100. Note, this rule shall work together with the non-overlapping rule. Hence, the smaller value between $\sqrt{2}D_{max}$ and $L_{i_{max}}$ can be chosen as the size for the segment, given by

$$L_i = min(\sqrt{2}D_{max}, L_{i_{max}}). \tag{4}$$

B. Channel Allocation

As mentioned in the system model, 7 non-overlapping channels on frequency are assumed, in order to increase the compatibility of the proposed scheme to existing MAC schemes. One channel is set as the Public Control Channel (PCCH); two channels are named Local Control Channels (LCCHs); and the rest 4 channels are used as Local Service Channels (LSCHs). In the system, vehicles initially work on AMCMAC [7]. To align the channels in AMCMAC, if no segmentation exists, PCCH is used as the control channel while the rest channels are service channels. In the MAC scheme by default, PCCH is used for broadcast of transmission requests/channel negotiations or emergency messages; one of the rest channels are used when a pair of nodes successfully make a channel negotiation. **Since the proposed algorithm targets to provide a local sub-network whenever the node density is found large, the number of nodes outside the segments is relatively small. Of course, there could be slight chances that a few nodes outside the segmented networks still working on all 7 channels, but the probability of collisions due to selecting the same channel at the timeslot as nodes in the segment is slim. The interference of such nodes to the segment networks is out of the scope of the paper.**

Once NCS decides to form a segment it informs the RSU via the other network interface (e.g., Ethernet, LTE-A). Then, segmentation information is broadcast periodically on the PCCH by the RSU. When a vehicle enters the V2X network, it always first listens to the PCCH before proceeding with any activity. When vehicles receive the segmentation information on the PCCH, vehicles update their own Segment ID (SID) according to the information, and switch to the corresponding LCCH immediately. Revocation information shall be disseminated both on

PCCH to inform newly joined nodes, and on LCCH to notice the nodes working on SMAC the cancellation of segmentation.

*1) **Intra-segment Connectivity**:* Nodes within the same segment are allocated with one LCCH and two LSCHs. The LCCH is used as the local control channels, on which emergency messages, channel negotiations and segmentation/revocation information are disseminated. LSCHs, on the other hand, are used for data transmissions among peers. Since only two service channels can be used for data transmissions in each segment, it is possible that both LSCHs are occupied and not available for another transmission. Thus, we allow the LCCH to be used for data transmission after a successful channel negotiation if both LSCHs are occupied at that moment. The channel access mechanism inside each segment could refer to our previous work [7].

*2) **Inter-segment Connectivity**:* Timely dissemination of emergency messages is crucial to all safety-related ITS applications. In this proposal, we aim to utilise RSUs to ensure fast dissemination of important V2X messages in multi-hop scenarios. Unlike the simple forwarding mechanism in most existing work [2], in SMAC, RSUs are made by default the forwarder for emergency messages. This reduces the collisions resulted in by multiple volunteering forwarders. It also speeds up forwarding process in large-scale networks. The detailed description and analysis of the fast information dissemination mechanism is given in Sec. IV.

In principle, the mechanism consists of two phases: assessment and forwarding. When an RSU receives an emergency message, it assesses the relevance of the message to the segment it belongs to. Emergency messages are usually of interest by nodes within several hops before expiration. For instance, if a hard break warning is broadcast in urban area, RSUs in nearby subnetworks may find the warning unrelated to the vehicles within its subnetwork. Therefore, the criterion for relevancy of an emergency message is use case specific. The V2X message will be forwarded by RSUs, only if the information is still useful for nodes inside their segments or adjacent segments. Emergency messages are immediately forwarded to other RSUs or dropped after the assessment.

*3) **Edge Effect**:* When the network is segmented as above, concerns arise from nodes moving towards the edges of segments. In the literature [17], it is already given that channel switch time takes about $150 \sim 200\mu s$. Suppose the vehicles move at the maximum speed but within the speed limits for highway, which is 70 mi/h (i.e., 31 m/s). The maximum distance during the channel switch is,

$$Dist_{max} = V_{max} \times \Delta t. \tag{5}$$

Hence, it means in highway scenarios, nodes may be absent for 0.62 cm on the edge of segments at most. For urban scenarios, since the speed limit is much lower than that of highway, vehicles could switch to the adjacent segment within 0.266 cm. Thus, the relatively small disconnection will not cause safety concern in terms of the edge effect.

IV. Delay Modelling for Multi-hop Dissemination

In this section, delay models of inter-segment connectivity are given, in order to evaluate the efficiency of multi-hop dissemination by SMAC. The analytical models demonstrate how the proposed scheme meets the stringent requirement of end-to-end delay in kinetic controlling use cases, and the substantial improvement of multi-hop dissemination latency comparing to the benchmark [2]. The term of dissemination delay means the latency from the first broadcast of an emergency message until the message is received by all vehicles within relevant hops.

The following assumption are made for the analytical modelling:

1) There are N identical active nodes in the reference area.
2) RSUs are deployed 500 m away from each other in a straight line.
3) 7 non-overlapping channels (10 MHz each) can be scheduled and allocated to different segments.

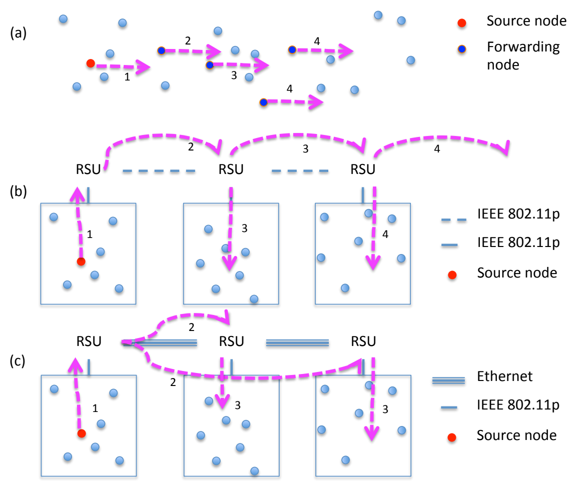

Fig. 5. Examples of Different Emergency Dissemination Procedures

A. Dissemination Procedures

The relevant reference area covers 1500 by 500 meters along the dissemination direction [25]. Since RSUs are assumed locating in a straight line, we simplify Eq. (2) to $L_{i_{max}} = 500m$ to reduce the analytical modelling complexity without losing generality. Random distribution is assumed for vehicles all over the reference area. Hence, if we define the average number of nodes in each segment as N_h, the total number we consider in the dissemination scenarios is roughly $3N_h$. Emergency messages are generated by vehicles which are equipped with kinematic/perception/environmental sensors. The traffic flows are demonstrated by the pink dash lines. Fig. 5 gives examples of the procedures of different dissemination modes.

(a) *Traditional infrastructure-free forwarding mode* [2]:

In mode (a), no infrastructure exists, hence the messages are forwarded and disseminated by volunteering forwarders. In the example, it can be seen that it is likely to trigger multiple forwardings for the same V2X message. In this case, emergency messages may be unnecessarily rebroadcast many times and meanwhile reduce the system performance in terms of end-to-end latency, throughput and packet delivery rate.

(b) *SMAC fast dissemination mode*

Mode (b) shows the proposed forwarding technique with the assistance of RSUs. Emergency messages are first delivered to the nearby RSU on LCCH. Then, the messages are forwarded to other RSUs within relevant hops by the local RSU, via wireless communications access technology (e.g., broadcast via DSRC, multi-cast via LTE). RSUs which receive the emergency messages will disseminate the information for both local vehicles via LCCHs and other RSUs via PCCH.

(c) ***SMAC fast dissemination (with wired connections) mode***

In mode (c), wired connections among RSUs are assumed to be available. The messages are conveyed to nearby RSUs within a large reference area. It is up to the RSU itself to decide whether the emergency message is still valid for vehicles in its range after receiving the message. The Ethernet connection among infrastructures is considered because it might be one of the promising implementation of future ITS [20]. The forwarding procedure of mode (c) is similar to that in mode (b). The difference is that RSU can inform all other RSUs (of interest of such message) with wired connections, at once. Hence, related RSUs could be noticed of the emergency message with bounded delay (e.g., $50 \sim 125 \mu s$ [29]).

B. Decomposition of End-to-end Delay

The delay models for the multi-hop dissemination process in mode (b)/(c) are formulated into three parts: (D-i) the delay on LCCH (to inform the local RSU); (D-ii) the delay on PCCH (dissemination among RSUs); and (D-iii) the delay on LCCH (for other RSUs to broadcast in their local segments).

(D-i) The first part of the latency is generated when the vehicle detects an emergency event and broadcasts the emergency message within its local segment on LCCH. The latency is due to the contention and collisions among N_h nodes in the same segment, denoted as D_{LCCH}, a.k.a. Intra-segment Dissemination Delay.

(D-ii) The second part of the delay comes from the contention among RSUs, plus new nodes which just enter the relevant areas but have not switched to corresponding LCCH yet. The number of RSUs and new nodes is relatively small and transmission attempts on PCCH are not frequent, hence collisions may seldom occur on PCCH. In addition, since the majority of messages transmitted on PCCH are broadcasted AC_0 messages, no acknowledgement is available. According to the enhanced distributed channel access (EDCA) backoff procedure [2], the AC_0 Contention Window (CW) size does not increase. Each node randomly selects a backoff timer in the range of $[0, CW_{min}[0]]$. As a result, the delay on PCCH can be simplified as follows,

$$\begin{cases} D_{PCCH} = AIFS[0] + CW_{min}[0]/2 \times aSlotTime, \\ AIFS[0] = AIFSN[0] \times aSlotTime + aSIFSTime \end{cases} \tag{6}$$

where $CW_{min}[0]$ denotes the minimum CW size for AC_0, which is 3 as in the standard IEEE 802.11p [2]; $AIFS[0]$ denotes the arbitration interframe space (AIFS) for AC_0; $AIFSN[0]$ is 2 set by the EDCA parameter table for AC_0; $aSlotTime$ is the duration of a slot time (13 μs); and $aSIFSTime$ is the length of short interframe spacing (SIFS), i.e., 32 μs. All the above parameters are standardised in [2].

(D-iii) Finally, RSUs try to disseminate the emergency message on their own LCCHs. The delay caused on LCCH for each RSU is denoted as D_{LCCH}, which is the similar to the first part of the delay on LCCH, a.k.a. Intra-segment Dissemination Delay.

C. Modelling for Intra-segment Dissemination Delay

The intra-segment dissemination delay D_{LCCH} will be derived in this section. First, a two-dimension Markov chain for a single access category is proposed in order to calculate the transmission probability for traffic of such access category. Then, the intra-segment dissemination delay is derived from the models for transmission/backoff in terms of a Z-transform domain linear system.

Parameters and a summary of major notations are given in Table. II.

TABLE II

NOTATIONS USED IN THE ANALYSIS

Notation	Definition
N_h	Average number of nodes within one hop
τ_m	Transmission probability of AC_m
R_m	Internal collision probability of access category m
P_{busym}	The probability that AC_m queue is not empty
P_{Am}	The probability that the node has a packet arrived in each AC queue in one slottime
P_{bfm}	The probability that the backoff timer reduces by 1 for AC_m
M	Maximum number of times the contention windows may be increased
$M+f$	Frame retry limit

*1) **Calculation of Transmission Probability**:* Following our previous work [10] which proposes an analytical model for the channel access per access category in IEEE 802.11p, we extend the model to make it adaptive to suit the scenarios with unsaturated traffic. Here, a two-dimensional Markov Chain is proposed to model the backoff process for an individual access category (AC), as shown in Fig. 6. Each state in this chain is represented by the tuple $[s(t), b(t)]$, where $s(t)$ is the backoff stage of a Head-Of-Line (HOL) packet for each AC at time t that corresponds to the number of collisions that the HOL packet has suffered up to time t, while $b(t)$ is the backoff counter at time t. To model the unsaturated traffic condition, a new state namely 'IDLE' is defined in the Markov Chain for each access category. In the scenarios, emergency messages (AC_0) and non-safety related packets (AC_1) are generated in Poisson process, i.e., each node generates traffic with an expected value of λ_m packets/sec for AC_m. Hence, the probability that

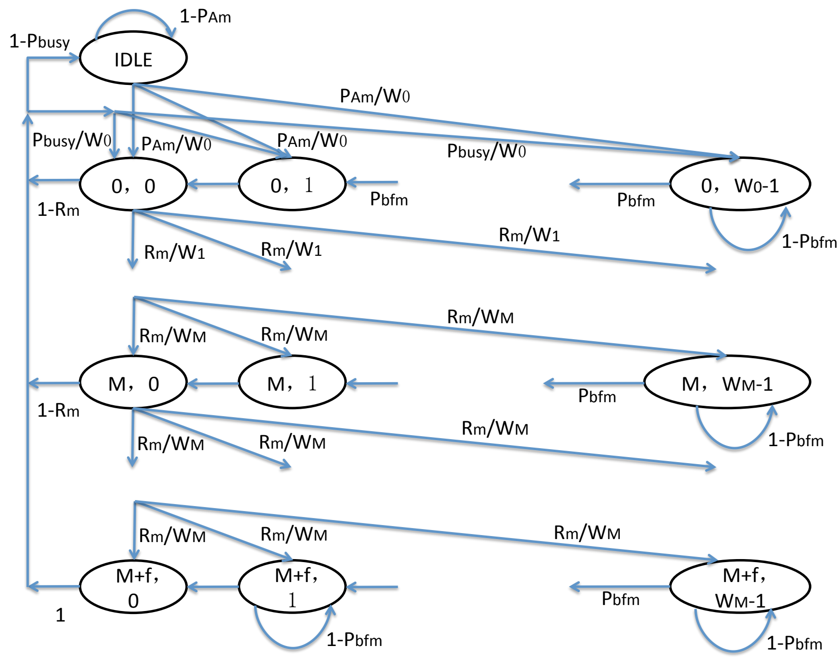

Fig. 6. Two-dimension Markov Chain for AC_m

the node has a packet arrived in each AC queue (i.e., the probability that the node leaves the "IDLE" state for one of the states on stage 0) can be calculated as,

$$\begin{cases} P_{A0} = 1 - e^{-\lambda_0 \sigma}, \\ P_{A1} = 1 - e^{-\lambda_1 \sigma}. \end{cases} \tag{7}$$

Denote P_{busym} as the probability that there is at least one packet waiting in the queue of AC_m; σ is the slottime. P_{busym} can be defined by the traffic generation rate λ_m and the corresponding expected packet service rate μ_m. μ_m can be derived following the iteration process as in [26].

$$P_{busym} = \frac{\lambda_m}{\mu_m}. \tag{8}$$

The internal transmission probability of AC_m is denoted by τ_m. The internal collision probabilities (R_m) of different access categories can be expressed as:

$$\begin{cases} R_0 = 0, \\ R_1 = \tau_0. \end{cases} \tag{9}$$

The probability that the backoff timer reduces by 1 for different access categories can be calculated by,

$$\begin{cases} P_{bf0} = (1-\tau_0)^{(N_h-1)}(1-\tau_1)^{N_h}, \\ P_{bf1} = (1-\tau_0)^{N_h}(1-\tau_1)^{(N_h-1)}. \end{cases} \tag{10}$$

Let (i,j) represent the event of being in state $[s(t)=i, b(t)=j]$ and $P(i,j|k,l)$ be the the probability of transition from state (k,l) in time t to state state (i,j) in time $t+1$. The transition probabilities in the Markov chain in Fig. 6 are given in the following.

$$\begin{cases} P(i,k|i,k+1) = P_{bfm}, \text{ for } 0 \le k \le W_i - 2,\ 0 \le i \le M+f \\ P(0,k|i,0) = \dfrac{(1-R_m)P_{busym}}{W_0}, \text{ for } 0 \le i \le M+f-1,\ 0 \le k \le W_0 - 1 \\ P(0,k|M+f,0) = \dfrac{P_{busym}}{W_0}, \text{ for } 0 \le k \le W_0 - 1 \\ P(i,k|i-1,0) = \dfrac{R_m}{W_i}, \text{ for } 0 \le k \le W_i - 1,\ 1 \le i \le M+f, \\ P(0,k|IDLE) = \dfrac{P_{Am}}{W_0}, \text{ for } 0 \le k \le W_0 - 1, \end{cases} \tag{11}$$

We analyse the Markov chain in Fig. 6 to obtain the transmission probability for AC_m queue in any given time slot. Let $b_{i,k}$ be the stationary probability of state $[s(t)=i, b(t)=k]$ in the Markov chain, i.e.,

$$b_{i,k} \triangleq \lim_{t\to\infty} P[s(t)=i, b(t)=k], \text{for } 0 \le i \le M+f,\ 0 \le k \le W_i - 1. \tag{12}$$

From the transition probabilities in Eq. (11), the process will transit from $[i,k+1]$ to $[i,k]$ with probability of P_{bfm}. Hence,

$$\begin{cases} b_{0,0} = b_{0,1}P_{bfm} + b_{IDLE}\dfrac{P_{Am}}{W_0} + \dfrac{P_{busy}}{W_0}\left((1-R_m)\displaystyle\sum_{i=0}^{M+f-1} b_{i,0} + b_{M+f,0}\right), \\ b_{0,1}P_{bfm} = b_{0,2}P_{bfm} + b_{IDLE}\dfrac{P_{Am}}{W_0} + \dfrac{P_{busy}}{W_0}\left((1-R_m)\displaystyle\sum_{i=0}^{M+f-1} b_{i,0} + b_{M+f,0}\right), \\ \vdots \\ b_{0,W_0-1}P_{bfm} = b_{IDLE}\dfrac{P_{Am}}{W_0} + \dfrac{P_{busy}}{W_0}\left((1-R_m)\displaystyle\sum_{i=0}^{M+f-1} b_{i,0} + b_{M+f,0}\right). \end{cases} \tag{13}$$

Thus, for any state at stage 0,

$$b_{0,k} = \frac{W_0 - k}{W_0 P_{bfm}} b_{0,0}. \tag{14}$$

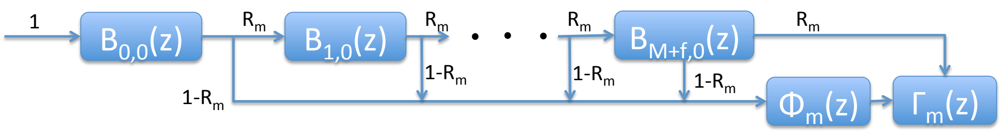

Fig. 7. Z-transform Linear System for AC_m

For any state on the other non-zero stages,

$$\begin{cases} b_{i,0} = b_{i,1} P_{bfm} + b_{i-1,0} \dfrac{R_m}{W_i}, \\ b_{i,1} P_{bfm} = b_{i,2} P_{bfm} + b_{i-1,0} \dfrac{R_m}{W_i}, \\ \vdots \\ b_{i,W_{i-1}} P_{bfm} = b_{i-1,0} \dfrac{R_m}{W_i}. \end{cases} \tag{15}$$

Thus,

$$b_{i-1,0} \cdot R_m = b_{i,0}, \quad \text{for } 1 \leq i \leq M+f. \tag{16}$$

Hence,

$$b_{i,0} = (R_m)^i \cdot b_{0,0}, \quad \text{for } 0 \leq i \leq M+f. \tag{17}$$

We could obtain the relationship between $b_{i,k}$ and $b_{i,0}$ from Eq. (15) as follows. For any state at other non-zero stages,

$$b_{i,k} P_{bfm} = \frac{W_i - k}{W_i} \cdot R_m \cdot b_{i-1,0}, \quad \text{for } 1 \leq i \leq M+f,\ 0 \leq k \leq W_i - 1. \tag{18}$$

From Eq. (16), we could rewrite Eq. (18) as,

$$b_{i,k} = \frac{W_i - k}{W_i P_{bfm}} b_{i,0}, \quad \text{for } 1 \leq i \leq M+f,\ 0 \leq k \leq W_i - 1. \tag{19}$$

Combining with Eq. (14), for $0 \leq k \leq W_i - 1$,

$$b_{i,k} = \frac{W_i - k}{W_i P_{bfm}} \cdot b_{i,0}, \quad \text{for } 0 \leq i \leq M+f. \tag{20}$$

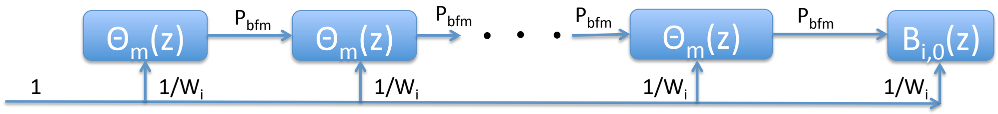

Fig. 8. Z-transform System Block Diagram for Backoff Instance for AC_m

The probability of IDLE state can be calculated as,

$$b_{IDLE} = b_{IDLE} \times (1 - P_{Am}) + (1 - P_{busy}) \times \left((1 - R_m) \sum_{i=0}^{M+f-1} b_{i,0} + b_{M+f,0}\right)$$

$$= \frac{1 - P_{busy}}{P_{Am}} \left((1 - R_m) \sum_{i=0}^{M+f-1} b_{i,0} + b_{M+f,0}\right) \tag{21}$$

Since the sum of all states in the Markov chain equals to one,

$$1 = \sum_{i=0}^{M+f} \sum_{k=0}^{W_i-1} b_{i,k} + b_{IDLE} = \sum_{i=0}^{M+f} \frac{b_{i,0}}{P_{bfm}} \sum_{k=0}^{W_i-1} \frac{W_i - k}{W_i} + \frac{1 - P_{busy}}{P_{Am}} \left((1 - R_m) \sum_{i=0}^{M+f-1} b_{i,0} + b_{M+f,0}\right)$$

$$= \frac{b_{0,0}}{2P_{bfm}} \left(\frac{1}{1 - R_m} + W_0 \sum_{i=0}^{M} 2^i R_m^i + W_M \sum_{i=M+1}^{M+f} R_m^i + \frac{2P_{bfm}(1 - P_{busy})}{P_{Am}}\right) \tag{22}$$

Hence,

$$b_{0,0} = 2P_{bfm} \left(\frac{1}{1 - R_m} + W_0 \sum_{i=0}^{M} 2^i R_m^i + W_M \sum_{i=M+1}^{M+f} R_m^i + \frac{2P_{bfm}(1 - P_{busy})}{P_{Am}}\right)^{-1} \tag{23}$$

A transmission occurs whenever the backoff counter becomes zero. Hence, the transmission probability for AC_m can be expressed by

$$\tau_m = \sum_{i=0}^{M+f} b_{i,0} = b_{0,0} \sum_{i=0}^{M+f} (R_m)^i = \frac{b_{0,0}}{1 - R_m}. \tag{24}$$

Replacing the $b_{0,0}$ in Eq. (24) by Eq. (23), the probability of transmission τ_m, can be obtained as follows.

$$\tau_m = \frac{2P_{bfm}}{1 - R_m} \left(\frac{1}{1 - R_m} + W_0 \sum_{i=0}^{M} 2^i R_m^i + W_M \sum_{i=M+1}^{M+f} R_m^i + \frac{2P_{bfm}(1 - P_{busy})}{P_{Am}}\right)^{-1} \tag{25}$$

*2) **Intra-segment Dissemination Delay**:* The next step is to derive intra-segment dissemination delay D_{LCCH}, namely the MAC serving time. The MAC service time denotes the duration from the moment that a packet becomes the HOL packet, to the time when the packet is successfully transmitted or dropped ([26], [27]). In the following derivation, γ_m is used to denote the MAC serving time for traffic of access category m. Fig. 7 depicts the whole transmission/backoff process in terms of a Z-transform domain linear system. The probability generating function (PGF) of the MAC service time can be obtained by,

$$\Gamma_m(z) = \sum_{x=0}^{\infty} \eta_{m,x} z^{\gamma_{m,x}}, \tag{26}$$

where $\eta_{m,x}$ is the probability for service time $\gamma_{m,x}$. Hence, the PGF can be evaluated via the transfer-function approach. Under the assumption that the packet sizes are the same for each AC, the transmission time of each packet is fixed as a constant. Thus, the PGF of the transmission time T_ϕ for AC_m is given by,

$$\Phi_m(z) = z^{T_{\phi m}}. \tag{27}$$

Thus, the PGF of the MAC service time is derived according to Fig. 7 as follows,

$$\Gamma_m(z) = R_m^{M+f+1} \prod_{k=0}^{M+f} B_{k,0}(z) + \Phi_m(z)(1-R_m) \sum_{k=0}^{M+f} B_{k,0}(z). \tag{28}$$

The mean MAC service time can be expressed by,

$$\overline{\gamma_{m,x}} = \frac{d\Gamma_m(z)}{dz}|z=1. \tag{29}$$

To obtain $\overline{\gamma_{m,x}}$, we first need calculate $B_{k,0}(z)$. In the backoff procedure, the backoff timer decreases by 1 if the medium is sensed idle; the timer is frozen for a period (i.e., T_{NAV}) if transmission is detected on the shared channel. The PGF of the average time that the backoff timer of AC_m decreases by one is

$$\Theta_m(z) = P_{bfm} z^{\sigma} + (1-P_{bfm}) z^{T_{NAV}+AIFS[m]}, \tag{30}$$

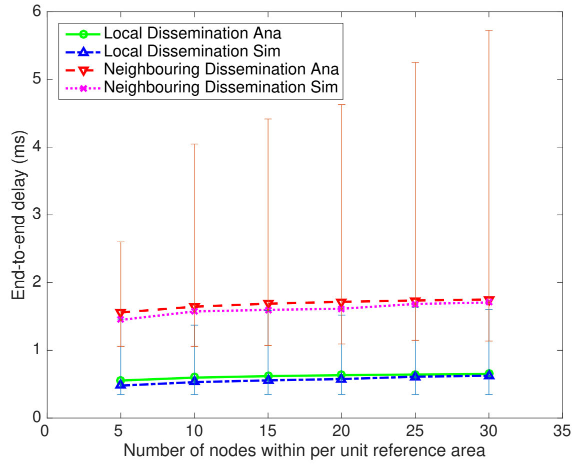

Fig. 9. Validation of Dissemination Delay Models

where T_{NAV} could be different due to the detected traffic types (e.g., emergency messages or non-safety related packets). From Fig. 8, the PGF $B_{i,0}(z)$ can be derived as,

$$B_{i,0}(z) = \frac{1}{W_i} \sum_{k=0}^{W_i-1} \Theta_m(z)^k. \tag{31}$$

To summarise, the total multi-hop dissemination delay will be a sum of the above derived delay (e.g., two intra-segment dissemination delay (i.e., $2 \times D_{LCCH}$) plus the delay on PCCH (i.e., D_{PCCH})) depending on the scenario, as decomposed in IV-B.

D. Validation of Analytical Modelling

The numerical models are validated against simulation results in this subsection. Denote, 'local dissemination' as emergency messages are disseminated within one segment; and 'neighbouring dissemination' as the emergency messages are delivered to vehicles in the neighbouring segment (i.e., one hop away from the local segment). 'Ana' and 'Sim' represents analytical and simulation results respectively in the context.

Fig. 9 validates the delay models for inter-segment dissemination mechanism (i.e., the multi-hop dissemination) in SMAC. The end-to-end delay from simulations with 95% confidence and

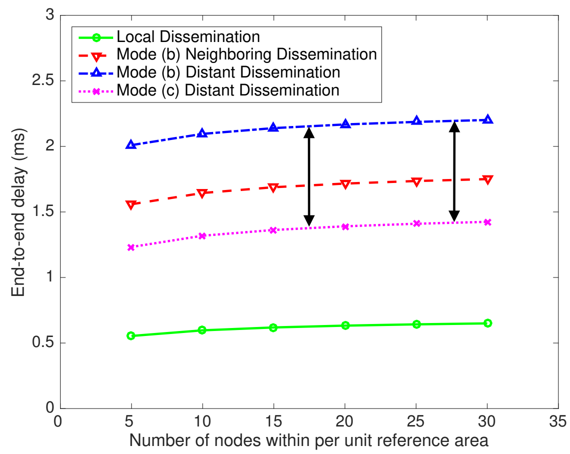

Fig. 10. Dissemination Delay of Mode (b) and (c) in Multi-hop Scenarios

analytical results are plotted against the number of nodes on average in each unit reference area for inter-segment dissemination mode (b). Both local dissemination and neighbouring dissemination delay are measured. It can be seen that the results from numerical analysis and the simulation results match each other.

Fig. 10 extends the delay measurement with 'Distant Dissemination' in order to demonstrate the benefits brought by alternative interfaces such as Ethernet in mode (c). Distant Dissemination refers to the case when emergency messages are disseminated in a large-scale area, e.g., several hops where the information in the message is still valid. A typical Ethernet connection latency is between 50 and 125 μs [29]. With this bounded latency, a fast dissemination of emergency messages can be guaranteed in large-scale dense scenarios. The benefit shown in Fig. 10 demonstrates about 50% latency reduction for dissemination within 3 hops. The benefit will be more remarkable in multi-hop dissemination cases.

V. Performance Evaluation

The proposed multi-channel MAC scheme is implemented by the authors and evaluated in the well-known simulation tool, NS-2 [22], from Lawrence Berkeley National Laboratory. The simulation scenario considers an urban area with dense traffic, where vehicles are randomly distributed in the grids. The average speed for the nodes is 27 mi/h, which is about the common speed limit for urban areas. The reference area covers 1500 m$\times$500 m, with 3 RSUs located on the central line. RSUs are assumed placed 500 m away from each other. Each RSU shall at least support the DSRC communications, and favorable to have an extra networking interface such as the Ethernet/cellular connections. Two scenarios are considered in this paper in order to keep the generality. Scenario 1 segments the whole reference area into 3 subnetworks; while scenario 2 only has two segmented networks on the sides and 1 open area in the middle. In open area, vehicles shall use the default MAC i.e. AMCMAC. Whenever the vehicle enters the segmented areas, it switches to SMAC. Each RSU equips two radios. One radio always stays with the PCCH for segmentation information dissemination, emergency messages rebroadcast, and multi-hop communication relay; while the other radio can be tuned between LCCH and LSCHs. The rest parameter settings are the same as in Sec. III.

Benchmarks are selected from both synchronous and asynchronous multi-channel schemes, namely, IEEE 1609.4 [21] (Synchronous), AMCP [23] (Asynchronous), and AMCMAC [11] (Asynchronous), to compare with the proposed scheme SMAC. Key Performance Indicators (KPIs) considered in this paper consist of throughput, packet delivery rate, packet collision rate, and penetration rate. Detailed discussion on each KPI is given in the following sub-sections.

A. *Throughput Performance Evaluation*

Fig. 11 shows the aggregate throughput against the total number of nodes in the large-scale reference area. The results illustrate that the SMAC (Scenario 1) outperforms other multi-channel MAC schemes in almost all scenarios (e.g., 33% improvement comparing to the second best), except in very sparse networks. It can be seen that each algorithm has throughput bound when the network is saturated. This again depends on the specific traffic loads in each AC queue and packet arrival rates. For SMAC and AMCMAC, due to the smart resource allocation, the saturated

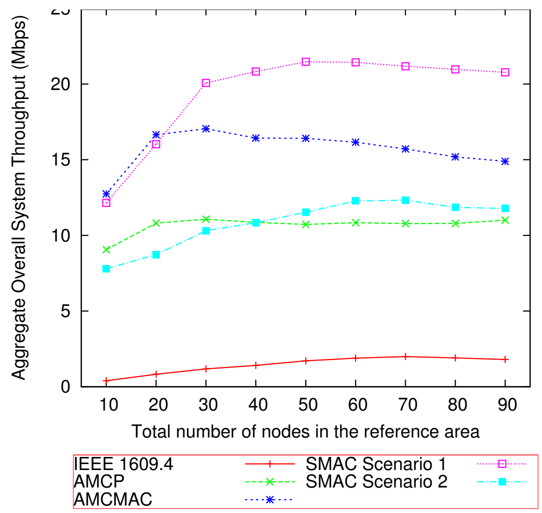

Fig. 11. Aggregate Throughput in Large-scale VANETs

throughput is much higher than the other benchmarks and is achieved in more dense networks. However, it is certain that not a single algorithm could fulfil unlimited transmission requests, hence, both SMAC and AMCMAC will eventually have a dropped throughput performance when the number of nodes in the network approaches infinity. SMAC Scenario 2 demonstrates poor performance comparing to SMAC Scenario 1 due to the vehicles in the middle area all stay on PCCH to compete for the channel access and negotiation. Other service channels are underutilised in such case.

To reduce the impact of lacking wrap-around modelling in simulations, the throughput achieved in the middle area of the reference network is measured. Fig. 12 shows the normalised throughput in the middle area against the total number of nodes. The proposed SMAC (Scenario 1) achieves much higher normalised throughput than the other three benchmarking multi-channel schemes in all scenarios, i.e., 280% enhancement to asynchronous multi-channel MACs (AMCP and AMCMAC) in the network consisting of 90 nodes. Again, SMAC Scenario 2 shows very quick degradation in terms of normalised throughput which basically presents the difference between using SMAC and AMCMAC for the vehicles in the middle area.

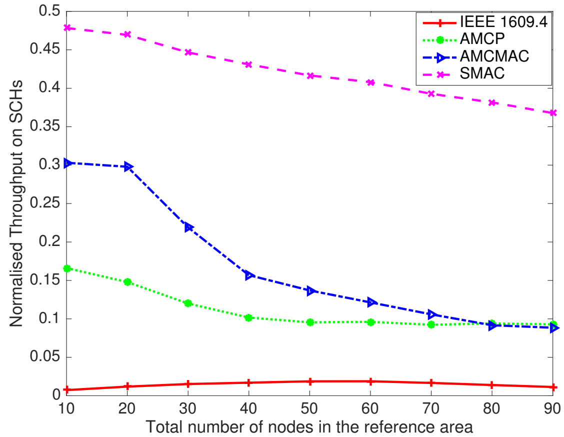

Fig. 12. Normalised Throughput in Large-scale VANETs

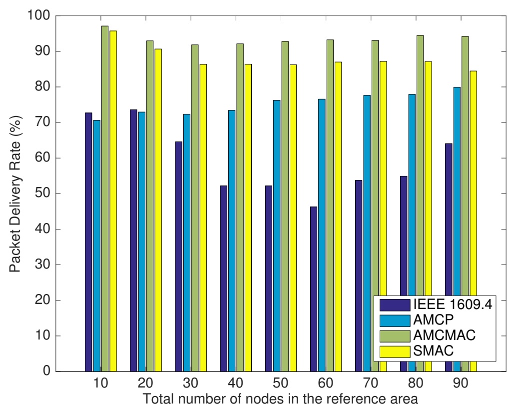

Fig. 13. The Packet Delivery Rates v.s. the Number of Nodes

B. Packet Delivery Rate and Collision Rate

Fig. 13 and 14 compare the packet delivery rates and collision rates on service channels/LSCHs. The SMAC and AMCMAC outperform the other two multi-channel MAC schemes, in terms of both packet delivery rates and collision rates. AMCMAC demonstrates higher packet delivery rates than SMAC (shown in Fig. 13 but achieves much lower throughput (shown in Fig. 11 and 12), due to the less active utilisation of the shared resources. AMCMAC achieves a higher packet delivery ratio than SMAC but a lower throughput, because in AMCMAC interference

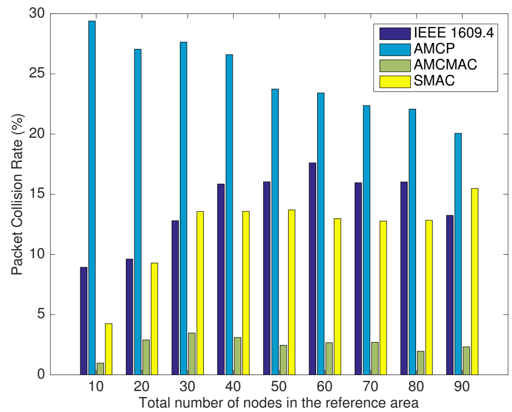

Fig. 14. The Packet Collision Rates on Service Channels v.s. the Number of Nodes

from exposed terminals makes the scheme difficult to successfully finish channel negotiation. Hence, fewer transmission attempts exist in AMCMAC comparing to SMAC. Although the packet delivery rate in AMCMAC is higher, the total number of packets to access the channel is much lower than SMAC. As for the collision rates, SMAC achieves lower collision rates comparing to AMCP and maintains a similar level of collisions as the standard IEEE 1609.4 does. The reason for AMCMAC achieving much lower collision rates than SMAC is the same as discussed in the above, that the AMCAC is weak in spectrum reuse and very reluctant to initiate a transmission attempt.

C. MAC Modes Switching

Penetration rate can be measured to evaluate the efficiency of dissemination of segmentation information in SMAC. The penetration rate is defined as the percentage of nodes that successfully receive the segmentation/channel allocation commands against potential receivers in the reference area. First, the accumulative penetration rates of segmentation information is measured against the times that the information is broadcast in Fig. 15. It is noted that usually after the first two broadcasts, the information can penetrate above half of the nodes in most scenarios. Fig. 16

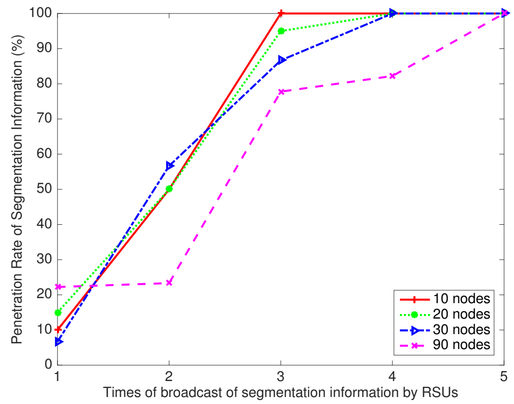

Fig. 15. The Accumulative Penetration Rates of Segmentation Information

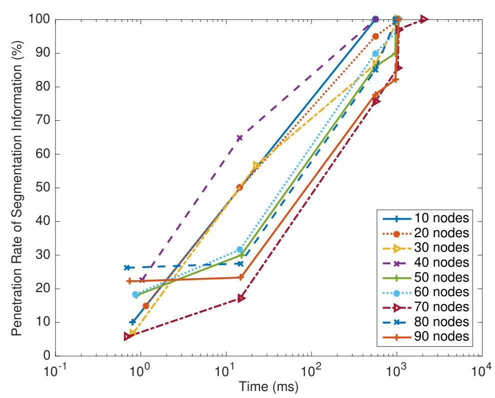

Fig. 16. The Penetration of Segmentation Information in Different Scales of Networks

shows the penetration rates against time in different network scales. All nodes can be informed about the segmentation of the reference network within 2 seconds (around 1 second for less congested scenarios). As a wrap-up, segmentation information reaches the intended vehicles within the tolerance. The mechanism of switching between SMAC and AMCMAC is suitable for large-scale dense vehicular networks.

VI. Conclusion

This paper addresses a significant challenge with respect to deployment of asynchronous multi-channel Dedicated Short Range V2X Communications in large-scale dense networks. The dynamic segmentation of large-scale networks and efficient allocation of channels across the network generate tremendous performance improvement, in terms of throughput, packet delivery rate, and collision rate. The proposed effective mechanism for inter-segment communications, can also significantly improve key performance indicators of the networks, such as multi-hop dissemination delay and packet delivery rate, as well as enhanced road safety. This work reveals the potential benefits adopting duel connectivity via numerical analysis. Future research with regard to Multi-RAT Heterogeneous Networks and Small Cells will add valuable contributions to the extension of the work.

Acknowledgement

This work was supported by Jaguar Land Rover and the UK-EPSRC grant EP/N01300X/1 as part of the jointly funded Towards Autonomy: Smart and Connected Control (TASCC) Programme.

References

[1] ABI Research, "V2V Penetration in New Vehicles to Reach 62% by 2027," Online: https://www.abiresearch.com/press/v2v-penetration-in-new-vehicles-to-reach-62-by-202/.

[2] "IEEE Standard for Information technology– Local and metropolitan area networks– Specific requirements– Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications Amendment 6: Wireless Access in Vehicular Environments," IEEE Std. 802.11p, pp. 1-51, 2010.

[3] 5GPPP, "5G Automotive Vision," 2015, Online: https://5g-ppp.eu/wp-content/uploads/2014/02/5G-PPP-White-Paper-on-Automotive-Vertical-Sectors.pdf.

[4] C. Han, M. Dianati, and M. Nekovee, "Effective decentralised segmentation-based scheme for broadcast in large-scale dense VANETs," *2016 IEEE Wireless Communications and Networking Conference (WCNC)*, Doha, 2016, pp. 1-6.

[5] Y. Bi, H. Shan, X. Shen, N. Wang, and H. Zhao, "A Multi-Hop Broadcast Protocol for Emergency Message Dissemination in Urban Vehicular Ad Hoc Networks," *IEEE Trans. Intell. Transp. Syst.*, vol. 17, no. 3, pp. 736-750, Mar. 2016.

[6] C. Suthaputchakun, Z. Sun, M. Dianati, “Trinary Partitioned Black-Burst-Based Broadcast Protocol for Time-Critical Emergency Message Dissemination in VANETs,” *IEEE Trans. Veh. Technol.*, vol. 63, no. 6, pp. 2926-2940, Jul. 2014.

[7] C. Han, M. Dianati, R. Tafazolli, and R. Kernchen, “Asynchronous Multi-Channel MAC for Vehicular Ad Hoc Networks,” *2011 IEEE Vehicular Networking Conference*, Amsterdam, 2011, pp. 170-176.

[8] T. Kosch, C. J. Adler, S. Eichler, C. Schroth, and M. Strassberger, “The scalability problem of vehicular ad hoc networks and how to solve it,” *IEEE Commun. Mag.*, vol. 13, no. 5, pp. 22-28, Oct. 2006.

[9] A. Brakemeier, “White Paper on Network Design Limits and VANET Performance,” Version 0.5, Car2Car Communication Consortium, Nov. 2008.

[10] C. Han, M. Dianati, R. Tafazolli, R. Kernchen and X. Shen, “Analytical Study of the IEEE 802.11p MAC Sublayer in Vehicular Networks,” *IEEE Trans. Intell. Transp. Syst.*, vol. 13, no. 2, pp. 873-886, Jun. 2012.

[11] C. Han, M. Dianati, R. Tafazolli, X. Liu and X. Shen, “A Novel Distributed Asynchronous Multi-Channel MAC Scheme for Large-Scale Vehicular Ad Hoc Networks,” *IEEE Trans. Veh. Technol.*, vol. 61, no.7, pp. 3125-3138, Sep. 2012.

[12] B. Kloiber, T. Strang, M. Rockl, and F. de Ponte-Muller, “Performance of CAM based safety applications using ITS-G5A MAC in high dense scenarios,” in *2011 IEEE Intelligent Vehicles Symposium (IV)*, 5-9 June 2011, pp.654-660.

[13] IEEE 802.11 Task Group AX, “Status of Project IEEE 802.11ax High Efficiency WLAN (HEW)”. Online: http://www.ieee802.org/11/Reports/tgax_update.htm, accessed May 2016.

[14] G. M. Abdalla, M. A. Abu-Rgheff and S. M. Senouci, “Space-Orthogonal Frequency-Time medium access control (SOFT MAC) for VANET,” *2009 Global Information Infrastructure Symposium, Hammemet*, 2009, pp. 1-8.

[15] S. Bana and P. Varaiya, “Space division multiple access (SDMA) for robust ad hoc vehicle communication networks,” in *IEEE Intelligent Transportation Systems 2001*, Aug. 2001, pp. 962-967.

[16] S. Katragadda, C. Ganesh Murthy, M. Ranga Rao, S. Mohan Kumar and R. Sachin, “A decentralized location-based channel access protocol for inter-vehicle communication,” *2003 Vehicular Technology Conference*, VTC 2003-Spring, Apr. 2003, pp. 1831-1835.

[17] J. Mo, H.-S. W. So, and J. Walrand, “Comparison of Multichannel MAC Protocols,” *IEEE Trans. Mobile Computing*, vol. 7, no. 1, pp. 50-65, 2008.

[18] F. Hou, L. X. Cai, X. Shen, and J. Huang, “Asynchronous Multichannel MAC Design With Difference-Set-Based Hopping Sequences,” *in IEEE Trans. Veh. Technol.*, vol. 60, no. 4, pp. 1728-1739, May 2011.

[19] R. Manzoku, H. Sekiya, J. Ma, K. Sanada, and S. Sakata, “An asynchronous multi-channel MAC protocol with Pulse/Tone exchange for RTS collision avoidance,” *2012 International Symposium on Telecommunication Technologies (ISTT)*,Kuala Lumpur, 2012, pp. 76-81.

[20] [Online]. Available: http://www.fotsis.com/

[21] IEEE Trial-Use Standard for Wireless Access in Vehicular Environments (WAVE) - Multi-Channel Operation, IEEE Std 1609.4-2006, 2006.

[22] [Online]. Available: http://www.isi.edu/nsnam/ns/

[23] J. Shi, T. Salonidis and E. W. Knightly, “Starvation mitigation through multi-channel coordination in CSMA multi-hop wireless networks,” *the 7th ACM international symposium on Mobile ad hoc networking and computing*, New York, NY, 2006, pp. 214-225.

[24] T. Luo, M. Motani and V. Srinivasan, “CAM-MAC: A Cooperative Asynchronous Multi-Channel MAC Protocol for Ad Hoc Networks,” *Proc. 3rd Int. Conf. Broadband Communications, Networks and Systems BROADNETS 2006*, 2006, pp. 1-10.

[25] D. N. M. Dang, H. N. Dang, C. T. Do and C. S. Hong, “An Enhanced Multi-channel MAC for Vehicular Ad Hoc Networks,” in *IEEE Wireless Communications and Networking Conference (WCNC)*, Apr. 2013, pp. 351-355.

[26] Y. Yao, L. Rao, X. Liu and X. Zhou, “Delay analysis and study of IEEE 802.11p based DSRC safety communication in a highway environment,” in *IEEE INFOCOM*, 2013, pp. 1591-1599.

[27] B. Xiang, M. Yu-Ming and X. Jun, “Performance Investigation of IEEE 802.11e EDCA under Non-saturation Condition based on the M/G/1/K Model,” in *IEEE Industrial Electronics and Applications*, 2007, pp. 298-304.

[28] Y. Cao, N. Wang and G. Kamel, “A Publish/Subscribe Communication Framework For Managing Electric Vehicle Charging,” *2014 IEEE ICCVE*, pp. 318-324.

[29] QLogic, “Introduction to Ethernet Latency-An Explanation of Latency and Latency Measurement”, QLogic Technology Brief, Aug. 2011.